

NGC 3801 caught in the act: A post-merger starforming early-type galaxy with AGN-jet feedback

Ananda Hota^{1,*}, Soo-Chang Rey², Yongbeom Kang^{2,3}, Suk Kim²,
Satoki Matsushita¹, Jiwon Chung²

¹ Academia Sinica Institute of Astronomy and Astrophysics, P.O. Box 23-141, Taipei 106, Taiwan, R.O.C.

² Department of Astronomy and Space Science, Chungnam National University, Daejeon 305-764, Republic of Korea

³ Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA

Accepted. Received

ABSTRACT

In the current models of galaxy formation and evolution, AGN feedback is crucial to reproduce galaxy luminosity function, colour-magnitude relation and $M_{\bullet}-\sigma$ relation. However, if AGN-feedback can indeed expel and heat up significant amount of cool molecular gas and consequently quench star formation, is yet to be demonstrated observationally. Only in four cases so far (Cen A, NGC 3801, NGC 6764 and Mrk 6), X-ray observations have found evidences of jet-driven shocks heating the ISM. We chose the least-explored galaxy, NGC 3801, and present the first ultraviolet imaging and stellar population analysis of this galaxy from GALEX data. We find this merger-remnant early-type galaxy to have an intriguing spiral-wisp of young star forming regions (age ranging from 100–500 Myr). Taking clues from dust/PAH, H_I and CO emission images we interpret NGC 3801 to have a kinematically decoupled core or an extremely warped gas disk. From the HST data we also show evidence of ionised gas outflow similar to that observed in H_I and molecular gas (CO) data, which may have caused the decline of star formation leading to the red optical colour of the galaxy. However, from these panchromatic data we interpret that the expanding shock shells from the young (~ 2.4 million years) radio jets are yet to reach the outer gaseous regions of the galaxy. It seems, we observe this galaxy at a rare stage of its evolutionary sequence where post-merger star formation has already declined and new powerful jet feedback is about to affect the gaseous star forming outer disk within the next 10 Myr, to further transform it into a red-and-dead early-type galaxy.

Key words: galaxies: active – galaxies: evolution – galaxies: individual: NGC 3801

1 INTRODUCTION

By incorporating feedback from star formation and AGNs into cosmological simulations, various puzzling statistical correlations of galaxies like the galaxy luminosity function, the $M_{\bullet}-\sigma$ relation, and the colour-magnitude bi-modality of nearby galaxies can be reproduced (Springel, Di Matteo & Hernquist 2005, Croton et al. 2006). In the models of galaxy evolution via merger, the abrupt separation between spiral, gas-rich, young star forming galaxies and their merger product gas-poor, old stellar population, elliptical galaxies requires AGN feedback to be playing a decisive role (Springel, Di Matteo & Hernquist 2005). Statistical studies of early-type galaxies (ETG) from Sloan Digitised Sky

Survey (SDSS) and Galaxy Evolution Explorer (GALEX) data argue in favour of a fast (within a billion year) quenching of star formation process driven by the Active Galactic Nuclei (AGN) feedback (Schawinski et al. 2007, Kaviraj et al. 2011). However, a direct observational evidence for an AGN-driven gas outflow or heating to have quenched the star formation process in any galaxy is still missing.

If in a sample of post-merger ETGs, star formation is found to be on the decline, mass outflow rate is larger than the ongoing star formation rate and AGN feedback timescale coincide with any sharp break in the star formation history, then the feedback-driven galaxy evolution hypothesis will get a substantial support. The UV-bright ETGs and the post-starburst galaxies could be the prime targets to look for relics of past AGN feedbacks. In this case, radio loud AGNs are probably the only kind of AGNs where the

* E-mail: hotaananda@gmail.com

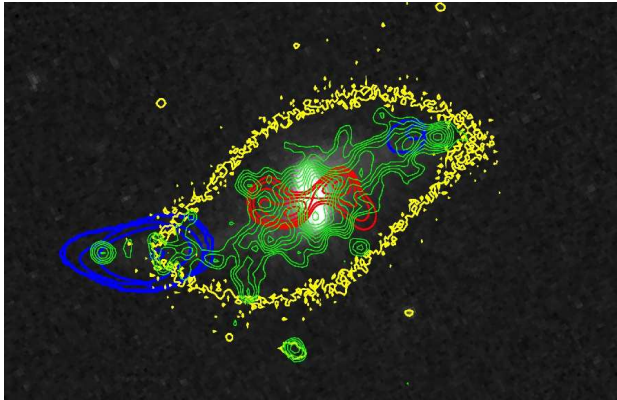


Figure 1. Panchromatic summary of NGC 3801 showing radio continuum (red), H I emission (blue), $8\ \mu\text{m}$ dust/PAH emission (gray scale), SDSS r' band single contour (yellow) and near UV (green) images, from various observations (Hota et al. 2009). See Das et al. 2005 and Croston et al. 2007 for CO and X-ray emission images, respectively.

relics of past AGN feedback, as relic lobe, can be investigated. Radio jets, often episodic in a few million years (Myr) timescale, may drive frequent and powerful gaseous outflows and shock-heating of the Interstellar Medium (ISM) to prevent star formation. From Chandra X-ray observations, so far, only four cases are known to show galactic-scale shocks driven by AGN-produced radio lobes, which are Cen A, NGC 3801, NGC 6764 and Mrk 6 (Mingo et al. 2011 and references therein). We chose to analyse the least explored galaxy, NGC 3801 (Croston et al. 2007), which is also the clearest case of kpc-scale shocks apparently buried within the rich ISM of the host galaxy, in an attempt to investigate galaxy evolution via merger, star formation and AGN-feedback processes.

NGC 3801: It has been known since very early time that it is an FR I, low-power, compact radio source ($\sim 40''$ or ~ 9 kpc) seen smaller than the optical host galaxy and likely to be buried within the ISM. The host galaxy has been classified S0/a and morphology is disturbed. It has one minor-axis dust-lane and another prominent dust filament extending from the centre to the eastern edge of the galaxy, roughly orthogonal to the dust-lane (Heckman et al. 1986, and references therein). The faint light distribution on the outer edges was also known to show boxy shape and a stellar tail on the south-eastern corner of the box. Within the box shape, the stellar light show an open S-shaped structure, more similar to the hysteresis loop. The radio lobes, also in the shape of S, is seen confined within this hysteresis loop structure (HLS), with similar clockwise bending (See Fig.1; Heckman et al. 1986).

Surrounding these radio lobes, shock shells have been discovered with the Chandra X-ray observations (Croston et al. 2007). These shock shells have been estimated to be expanding at a velocity of $850\ \text{km s}^{-1}$ and material driven away by it may escape from the ISM of the galaxy. Cool molecular gas emission, traced by CO (1-0), has been imaged by Das et al. (2005). This revealed three clumps, two roughly on the minor-axis dust lane, suggesting rotating gas disk ($r = 2$ kpc), and the third clump on the eastern filament at similar radial distance. Atomic hydrogen emission (H I 21cm

line), first detected by Heckman et al. (1983), has recently been imaged by Hota et al. 2009 (hereafter Hota-09), who suggest a 30 kpc size gas disk rotating along the major axis of the galaxy (Fig. 1, blue contours).

Ultraviolet (UV) light traces the young star formation and has potential to tell stories of the last major episode of star formation in an ETG and its interplay with the AGN. In this *letter* we present the first UV imaging study and investigation of the stellar population of this galaxy, from the archival GALEX data. We discuss our findings of this interesting target, a prime candidate to understand galaxy evolution by merger, star formation and AGN feedback, incorporating all available panchromatic information. For a systemic velocity of $3451\ \text{km s}^{-1}$, we adopt a distance of 47.9 Mpc to NGC 3801, corresponding to the angular scale of $1'' = 0.23$ kpc. For easy comparison with X-ray and molecular gas images published earlier we have presented all the images in B1950 co-ordinate system.

2 UV OBSERVATIONS AND DATA ANALYSIS

NGC 3801 was imaged with GALEX in both the far-ultraviolet (FUV; $1350\text{--}1750\ \text{\AA}$) and near-ultraviolet (NUV; $1750\text{--}2750\ \text{\AA}$). We extracted the UV images of NGC 3801 from the GALEX Release 5 (GR5) archive. The total integration times were 111 s and 265 s for FUV and NUV, respectively. The GALEX instruments and their on-orbit performances and calibrations are described by Morrissey et al. (2007 and references therein). GALEX FUV and NUV imaging has $4''.2$ and $5''.3$ resolution (FWHM) which corresponds to ~ 0.97 kpc and 1.2 kpc, respectively. In NUV and FUV images, we defined UV bright clumps to trace their morphology and to measure their UV flux densities. The images were adaptively smoothed using the Gaussian filter by 3 pixel ($\sim 5''$) radius in order to select morphologically distinct clumps. Various thresholds above the mean sky background value were applied for delineation of the clumps. We detect 9 clumps in the smoothed NUV image each of which has at least 10 contiguous pixels. We measured UV flux within the contours of the clumps, and subtracted the local background using the GALEX GR5 pipeline background image (“skybg”). Finally, FUV and NUV magnitudes in the AB magnitude system and photometric errors of all clumps were determined (see Table 1). Foreground Galactic extinction was corrected using the reddening maps of Schlegel, Finkbeiner & Davis (1998) and the extinction law of Cardelli, Clayton & Mathis (1989).

3 RESULTS

UV morphology: The smoothed NUV image shows an intriguing S-shaped morphology (Fig. 2 top panel). In contrast to the optical morphology (Fig.1 yellow contour), where the envelope of the stellar light was HLS, here this S-shaped NUV spiral-wisp is seen as the central spine of the optical HLS. Some diffuse and fainter emission is also seen in the intermediate region between spiral-wisp and the HLS. The western wisp is brighter than its eastern counterpart, but they extend up to similar distances ($60''\text{--}70''$ or $14\text{--}16$ kpc)

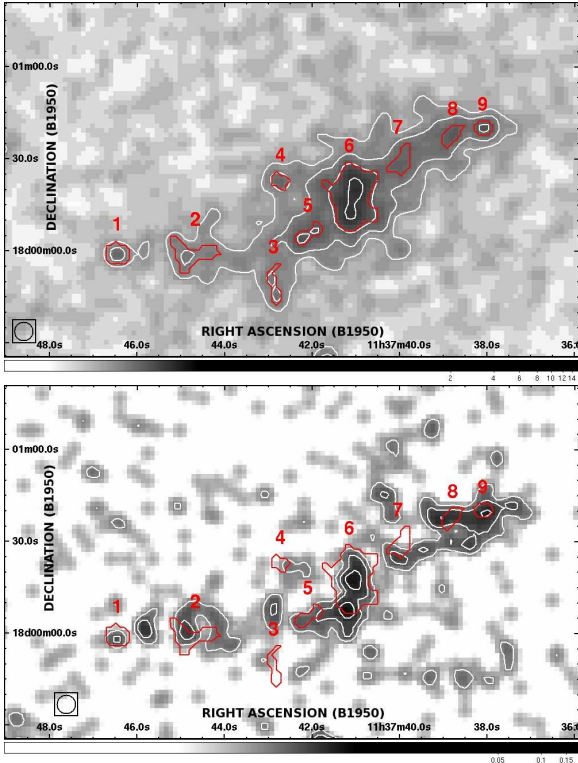


Figure 2. Smoothed near UV (top panel) and far UV (bottom panel) image of NGC 3801, presented both in linear gray scale and white contours. Regions selected for stellar population age-analysis, from the NUV image, have been marked in red contours and labelled 1 to 9.

Table 1. Photometry and Age Estimation of the UV Clumps

clump no.	far UV AB mag	near UV AB mag	Age Myr Z=0.02	Age Myr Z=0.05
1	22.678 \pm 0.433	21.808 \pm 0.175	371 \pm 131	332 \pm 134
2	21.921 \pm 0.304	21.135 \pm 0.129	349 \pm 90	311 \pm 93
3	23.555 \pm 0.699	21.842 \pm 0.175	527 \pm 127	475 \pm 100
4	23.430 \pm 0.620	22.164 \pm 0.200	455 \pm 142	416 \pm 128
5	22.122 \pm 0.320	21.478 \pm 0.142	311 \pm 131	289 \pm 140
6	20.419 \pm 0.148	19.364 \pm 0.053	413 \pm 33	390 \pm 32
7	23.045 \pm 0.532	21.510 \pm 0.148	499 \pm 97	458 \pm 84
8	21.929 \pm 0.290	21.756 \pm 0.164	111 \pm 469	85 \pm 364
9	22.094 \pm 0.311	21.915 \pm 0.174	114 \pm 509	92 \pm 409
10	18.724 \pm 0.071	17.696 \pm 0.026	408 \pm 16	362 \pm 15

from the centre of the galaxy. NUV wisps connect to an elongated bright structure at the centre, oriented nearly north-south. It is as bright in surface brightness as any compact emission on the spiral-wisp. This central elongated structure does not show any strong peak at the centre, but extends $\sim 15''$ (3.5 kpc) on either side of the centre. This elongated emission can be compared with the minor axis dust-lane but its detail structure and orientation differs. Although the major axis extension in optical and UV are comparable, the UV emission along the minor-axis is smaller, nearly half of the optical HLS (Fig. 1). We also present the FUV image smoothed to same resolution (Fig. 2 bottom panel).

Although this shows similar spiral-wisp structure as in NUV, it looks clumpier and noisier. Unlike in NUV, the FUV emission is centrally peaked (R.A. 11h 37m 41.1s Dec. $+18^\circ 00' 16''$), and is closer to the centre of the galaxy (R.A. 11h 37m 41s.2 Dec. $+18^\circ 00' 18''$; derived from IR images). Since UV traces the recent massive star formation, this spiral-wisp, seen as a curved spine to the HLS, is likely a distinct newly formed structure containing relatively young stars.

Age of the stellar population: Small clumps along the spiral-wisp labelled 1 to 9 (Fig. 2) and the whole emission region, for the galaxy, assigned a number 10 have been chosen for extracting photometric parameters. It is unclear if clumps 1 and 9 are part of NGC 3801 or independent galaxies, therefore for our analysis they have been excluded from determining global parameters of NGC 3801. Although there is no complete overlap between the NUV and FUV images for a few clumps, still we went ahead in our analysis for a representative value of the age of stellar population. We estimated luminosity-weighted average ages for the stellar population in clumps along the spiral-wisp by comparing FUV-NUV color with synthetic population models of Bruzual & Charlot (2003). In Table 1 we present the ages of the clumps derived based on the models of simple stellar population (i.e. single burst star formation). Two different metallicity values, $Z = 0.02$ ($\text{Fe}/\text{H} = +0.0932$) and $Z = 0.05$ ($\text{Fe}/\text{H} = +0.5595$) were assumed for the age estimations and listed in separate columns. The errors are calculated using propagation of photometric errors. The stellar population age, ranges from 100 to 500 Myr for metallicity $Z = 0.02$ and slightly lower for a higher metallicity. Clump 8 associated with bright UV emission region on the western spiral-wisp, shows very young, 85–110 Myr stellar population, although the error bars are very large. Clumps 2, 3, 5, 7, and 8 show an average age ~ 300 Myr, demonstrating recent star formation along the spiral-wisp. No significant trend of stellar age with the distance from the nucleus was noticed. The central $20''$ (4.6 kpc) region of the galaxy (clump 6) with typical age of 400 ± 30 Myr, ignoring the effect of the AGN represent the most luminous star forming region. Since NGC 3801 as a whole has a similar ~ 400 Myr age stars, this suggests a recent star formation in this early-type radio galaxy host with many peculiar optical morphologies. Two clumps 1 and 9, as described earlier, show average stellar age of $\sim 350 \pm 130$ Myr and 100 ± 450 Myr respectively. Coincidental location at the ends of the spiral-wisp and similarity of stellar ages of these two clumps with that of the spiral-wisp, suggests that they are likely young star forming regions associated with NGC 3801.

4 DISCUSSION

Origin of the spiral-wisp: To understand the origin of the young star forming UV bright spiral-wisp, we need to take clues from the imaging and spectroscopy done at other wavelengths. Hence, in Fig. 1, we have summarised the NUV emission map, from the GALEX (green contours), optical r' band single contour image of the HLS, from the SDSS (yellow contours), dust and PAH emission image at $8 \mu\text{m}$, from the *Spitzer Space Telescope* (gray scale), and H α emission moment-0 map (blue contours) and 1.4 GHz radio continuum image, both from the Very Large Array (red con-

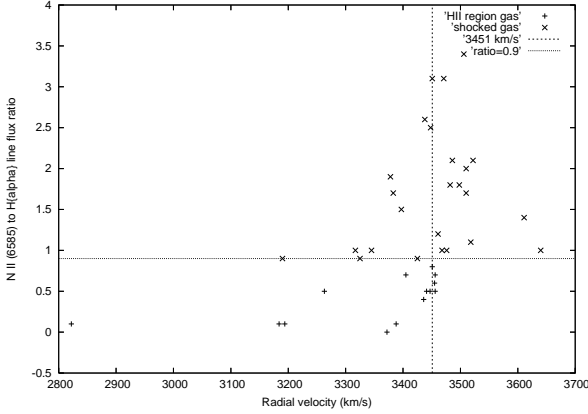


Figure 3. N II (6585) to H α line flux ratios have been plotted against the radial velocity of the emission components. Data has been taken from Noel-Storr et al. (2003). The lower (<0.9) and higher line ratios are marked with ‘+’ and ‘x’ signs, respectively. The horizontal and vertical lines mark ratio = 0.9 and $V_{\text{sys}} = 3451 \text{ km s}^{-1}$, respectively.

tours), of the galaxy for a panchromatic analysis. Readers are referred to Das et al. (2005) and Croston et al. (2007) for CO emission and X-ray emission images, respectively. The spiral-wisp clearly fits in as central spine to the HLS. The HLS, an atypical stellar distribution in an ETG like NGC 3801, deserves a kinematic modeling to be explained properly. On the eastern and western ends of the HLS, blobs of rotating HI represent a $\sim 30 \text{ kpc}$ size gas disk (Hota-09). On the other hand, within the central 4 kpc, CO emission clumps suggest rotating molecular gas disk oriented roughly north-south (Das et al. 2005). Two orthogonally rotating gas disks can not co-exist, radial location has to be different. This resembles a gas dynamical condition as seen in Kinetically Distinct/Decoupled Cores (KDC; Barnes 2002). In this KDC interpretation, the red-shifted eastern molecular cloud clump of Das et al. could be re-interpreted as part of the outer gas disk rotating along the optical major axis. As mentioned in Hota-09, although the HI rotates in the same sense as the stars, gas rotate twice faster than the stars. Both these forms of decouplings reinforce the idea of a merger origin of NGC 3801 (Barnes 2002, Heckman et al. 1986).

Alternate to a KDC, it can also be interpreted as an extremely ($\sim 90^\circ$) warped gas disk. The central north-south gas disk changes its orientation to east-west, with the increase of radius from 2 kpc to 15 kpc. The central 2 kpc molecular gas disk has a corresponding bright linear feature in the UV as well as in the dust/PAH emission. Similarly, the full spiral-wisp of UV emission also has a correspondence in the dust/PAH emission observed by the *Spitzer* (Fig. 1, Hota-09, Hota et al. in preparation). The HLS may possibly be reproduced if light from a low level star formation in the warped gas disk is added onto the dominant elliptical distribution of stellar light. Furthermore, if the gas disk is twisted or due to the projection effect, an inclined warped disk can reproduce the spiral-wisp of higher density and younger stars just along the line of orbital crowding. The brighter western part of the spiral-wisp is likely in the foreground and the eastern counterpart in the background. A direct comparison of the spiral-wisp can be seen in the galaxy NGC 3718,

where the warped, inclined and twisted gas disk has been kinematically modeled in detail using HI emission velocity field (Sparke et al. 2009). More sensitive HI and CO imaging of NGC 3801 will be very helpful to test our proposal.

State of star formation: As the last major phase of star formation in the galaxy happened $\sim 400 \text{ Myr}$ ago, the star formation process now is on the decline. When UV satellite data is not available, $u'-r'$ optical colour of galaxies, is often used as a proxy for starformation history, in large sample studies (e.g. Schawinski et al. 2007). The $u'-r'$ colour and r' band absolute magnitude of NGC 3801, as listed in the DR7, are 3.08 and -21.27 . This puts NGC 3801 clearly in the location of ‘red sequence’ or ‘red-and-dead’ type of galaxies (Strateva et al. 2001, Bell et al. 2004). From a large sample study of morphologically selected ETGs from the SDSS, Schawinski et al. (2007) proposed an evolutionary sequence in which star forming ETGs quickly transform to a quiescent red-galaxy phase via. an increasingly intense AGN activity over a period of one billion year. Young star formation in ETGs are usually found in the form of UV-bright rings and the spiral-wisp seen in NGC 3801 is bit unusual (Salim & Rich 2010). An important question arises, if this unusual UV morphology as well as the decline of star formation activity is related to any possible feedback processes from a past AGN or starburst superwind, and the galaxy is caught while changing.

Signatures of feedback: The eastern molecular gas clump seen superposed on the eastern jet was interpreted as partially jet-entrained (outflow) gas by Das et al. (2005). Presence of broad blue-shifted HI-absorption line seen against the same eastern radio jet was also mentioned by Hota-09 as a sign of outflow. We looked for further kinematic signatures of gaseous feedback in it. In Fig. 3 we plot the radial velocity of the emission line components and their N II (6585) to H α line flux ratio, extracted from the central $1''.8 \times 0''.4$ ($0.4 \times 0.1 \text{ kpc}$) region of NGC 3801 (from the *Hubble Space Telescope* (HST) data in the table 14 of Noel-Storr et al. 2003). Components with line ratio less than 0.9, which would suggest HII-region like ionised gas property, show a different distribution from components with higher line ratio representing ionisation by shocks (e.g. Veilleux & Rupke 2002). While the higher line ratio shocked gas is symmetrically distributed around the V_{sys} , the lower line-ratio gas is either near V_{sys} or significantly blue-shifted. The maximally blue-shifted (by 630 km s^{-1}) component also has the highest H α line flux ($21.4 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$) and the highest velocity dispersion (205 km s^{-1}). Absence of red-shifted component is likely due to extinction but the highly blue-shifted components clearly suggest outflow of ionised gas from the very central region. Whether this is directly related to AGN wind/jet, starburst superwind or outwardly moving shells during merger activity is unclear.

State of AGN activity: Schawinski et al. (2007) suggest that AGN activity peaks $\sim 500 \text{ Myr}$ after the peak star formation activity. With a glance through the SDSS DR7 spectral line data, we found that NGC 3801 can be classified in between Seyferts and LINERs ($\log(\text{NII}/\text{H}\alpha) = 0.138$ and $\log(\text{OIII}/\text{H}\beta) = 0.538$). This particular fact, $u-r$ colour and the stellar velocity dispersion of 225 km s^{-1} (de Nella et al. 1995), suggest that NGC 3801 is near the last phase of AGN activity prior to reaching a quiescent phase as per the evolutionary plot of figure 7 in Schawinski et al. (2007).

There is no clue as to how long the AGN activity has been in existence. Spectral ageing of the radio lobes is probably the only method of age-dating AGNs, if radio-loud. Croston et al. have estimated the spectral age from the steepest regions in the extended lobes or wings, where the oldest radio plasma is expected. Their spectral age of ~ 2.4 Myr is only suggesting a time-scale since when fresh relativistic plasma supply to the wings has been stopped. Hence, it is possible that wings may have been in existence since several tens of Myr. We also do not know the real orientation of the wings of the radio lobes, it may be much longer than what we see in projection. On the other hand the straight part of the radio jets, are visible in the sub-mm wavelengths, from which Das et al. interpret that the jets are expanding in the plane of the sky.

In the figure 2 of Croston et al. (2007) it is clear that the wings extends farther than the X-ray emitting shock shells. If wings are deflected hydrodynamic flow of the jets, they can not travel farther than the shock front. Hence, wings are older and shock is associated only with the current (younger than 2.4 Myr) jet activity. This jet is clearly orthogonal to the central minor-axis gas disk ($r = 2$ kpc). In a case (3C 449) where nuclear dust disk is warped, Tremblay et al. (2006) has discussed about the cause-effect ambiguity between the jet to have shaped the warped dust/gas disk or the reverse. Gopal-Krishna et al. (2010) suggest rotating ISM as a possible cause of wing formation, taking NGC 3801 as an example. As proposed for X-shaped radio galaxies (Gopal-Krishna et al. 2010), it is also possible that a recent binary black hole coalescence may have caused fast (within last 2.4 Myr) change of jet axis in NGC 3801.

Caught in the act: It is intriguing that the eastern dust filament, stops at the centre, with no extension to the west. Symmetry is expected due to rotation along the major axis. The HI-gas rotation period of ~ 330 Myr (for $r = 15$ kpc and $v = 280$ km s $^{-1}$; Hota-09) suggest that these dust filament and star forming UV-clumps are likely too young to have east-west symmetry. Similarly, lack of UV emission on the north-eastern and south-western quadrant of the galaxy, where wings of the radio lobes are seen, on projection, also present a curious co-incidence. In the fine dust silhouette image from the HST data (figure 5 of Das et al.) there is no signature of the effect from the radio jet, wing or shock shells. As the shock is associated only with the jet (younger than 2.4 Myr) expanding in the plane of the sky, it is very likely that it is yet to reach the outer parts of the host galaxy where dust filaments are present. In the warped gas disk geometry, the jets and shock are also likely to miss impacting on the outer gas disk in the early-phase. However, with an expansion velocity of 850 km s $^{-1}$ the shock can move 8 kpc in the next 10 Myr and can affect the outer gas (HI and CO) and dust distribution. It is unclear, if the past AGN activity had an effect on the host galaxy gas distribution and star formation; however, the current jet-induced shock shells are powerful enough to do it. We are likely witnessing this merger-remnant ETG just 10 Myr prior to its AGN-jet feedback start disrupting its outer gas disk and potentially quench its star formation.

Future directions: Since the star formation has started declining a few 100 Myr back and the oldest plasma in the radio lobes is only 2.4 Myr old, we fail to connect if AGN-feedback is the cause behind the declining/quenching

of star formation. Future studies need to include objects where AGN feedback and star formation processes are on comparable time-scale and directly interacting to investigate the causal connection. For example, in the radio bright Seyfert galaxy NGC 6764, the central 2 kpc radio bubble outflow and its associated shock-heated hot gas, warm ionised gas, cool molecular and HI gas outflow has a dynamical timescale of 10–20 Myr (same as the precession timescale of the radio jet). Interestingly, this is coincident with a break in the star formation history of the central region, which occurred 5–15 Myr ago. It is tempting to ask if the outflow has caused the break in star formation (Hota & Saikia 2006, Croston et al. 2008, Kharb et al. 2010). There is a need of observational programmes to bridge the gap by catching the recent most star formation history with optical spectroscopy, molecular gas loss history say with ALMA, and hunt for the radio relics of the oldest (up to several hundred Myr) episodes of AGN feedback. Deep low frequency radio surveys, like the ongoing TGSS at 150 MHz and upcoming LO-FAR sky surveys, may reveal relics of past AGN feedbacks in many post-starburst (Goto T. 2005), young star forming ETGs to better understand merger and feedback driven galaxy evolution (see a potential demonstrator in Hota et al. 2011).

REFERENCES

- Bruzual G., Charlot S., 2003, MNRAS, 344, 1000
 Barnes J.E., 2002, MNRAS, 333, 481
 Bell E.F., et al., 2004, ApJ, 608, 752
 Cardelli J.A., Clayton G.C., Mathis J.S., 1989, ApJ, 345, 245
 Croston J.H., Kraft R.P., Hardcastle M.J., 2007, ApJ, 660, 191
 Croston J.H., Hardcastle M.J., Kharb P., Kraft R.P., Hota A., 2008, ApJ, 688, 190
 Croton D.J., et al., 2006, MNRAS, 365, 11
 Das M., Vogel S.N., Verdoes Kleijn G.A., O’Dea C.P., Baum S.A., 2005, ApJ, 629, 757
 Gopal-Krishna, Biermann P.L., Gergely L.A., Wiita P.J., (2010arXiv1008.0789G)
 Goto T., 2005, MNRAS, 357, 937
 Heckman T.M., Balick B., van Breugel W.J.W., Miley G.K., 1983, AJ, 88, 583
 Heckman T.M., et al., 1986, ApJ, 311, 526
 Hota A. & Saikia D.J., 2006, MNRAS, 371, 945
 Hota A., Lim J., Ohya Y., Saikia D. J., Dihi-v-Trung, Croston J.H., 2009, ASPC, 407, 104 (Hota-09)
 Hota A., et al., 2011, MNRAS, 417L, 36
 Kaviraj S., Schawinski K., Silk J., Shabala S.S., 2001, MNRAS, 415, 3798
 Kharb P., et al., 2010, ApJ, 723, 580
 di Nella H., Garcia A.M., Garnier R., Paturel G., 1995, A&AS, 113, 151
 Mingo B., et al., 2011, ApJ, 731, 21
 Morrissey P. et al., 2007, ApJS, 173, 682
 Noel-Storr J. et al., 2003, ApJS, 148, 419
 Salim S. Rich R.M., 2010, ApJ, 714L, 290
 Schawinski K., et al., 2007, MNRAS, 382, 1415
 Schlegel D.J., Finkbeiner D.P., Davis M., 1998, ApJ, 500, 525
 Sparke L.S., van Moorsel G., Schwarz U., Vogelaar M., 2009, AJ, 137, 3976
 Springel V., Di Matteo T., Hernquist L., 2005, MNRAS, 361, 776
 Strateva I., et al., 2001, AJ, 122, 1861
 Tremblay G.R., et al. 2006, ApJ, 643, 101
 Veilleux S. & Rupke D.S., 2002, ApJ, 565L, 63